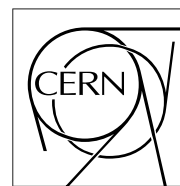


The Compact Muon Solenoid Experiment

CMS Note

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Coherent Interactions with heavy ions at CMS

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General Introduction

The physics of central collisions is the physics of the Quark Gluon Plasma. Apart from projects like the search for new physics at very high rapidities (see the CASTOR subproject at ALICE for a search for Centauro events at LHC [1]), “Non QGP Physics” may be defined as the physics of peripheral collisions, which includes the effects of coherent photons and diffraction effects (Pomeron exchange). It is our aim to show that one will be able at CMS to address very interesting physics topics in a rather clean way.

Central collision events are characterized by a very high multiplicity. On the other hand, the multiplicity in peripheral collisions is comparatively low. The ions do not interact directly with each other and move on essentially undisturbed in the beam direction. The only possible interaction are therefore due to the long range electromagnetic interaction and diffractive processes. Due to the coherent action of all the protons in the nucleus, the electromagnetic field is very strong and the resulting flux of equivalent photons is large. It is proportional to Z^2 , where Z is the nuclear charge. Due to the very short interaction times the spectrum of these photons extends up to an energy of about 100 GeV in the laboratory system. The coherence conditions limits the virtuality of the photon to very low values of $Q^2 < 1/R^2$, where $R = 1.2 fm A^{1/3}$ is the nuclear size.

Hard diffractive processes in heavy ion collisions have also been studied. These are interesting processes on their own, but they are also a possible background to photon-photon and photon-hadron interactions. The physics potential of such kind of collisions is discussed in Section 1 (this is an extension of CMS note1998/009). It ranges from studies in QCD and strong field QED to the search for new particles (like a light Higgs particle). This kind of physics is strongly related to $\gamma\gamma$ physics at e^+e^- -colliders with increased luminosity. In view of the strong interaction background, experimental conditions will be somewhat different from the $\gamma\gamma$ physics at e^+e^- -colliders. A limitation of the heavy ions is that only quasireal but no highly virtual photons will be available in the A-A collisions.

Another aspect is the study of photon-hadron interactions, extending the γ -p interaction studies at HERA/DESY to γ -A interactions, also reaching higher invariant masses than those possible at HERA.

At the STAR (Solenoidal Tracker At RHIC) detector at RHIC — to be scheduled to begin taking data in 1999 — a program to study photon-photon and Pomeron interactions in peripheral collisions exists [2, 3, 4, 5, 6]. At RHIC the photon flux will be of the same order of magnitude, but the spectrum is limited to up to about 3 GeV.

1 Photon-Photon and Photon-Hadron Physics

1.1 Abstract

Due to coherence, there are strong electromagnetic fields of short duration in very peripheral collisions. They give rise to photon-photon and photon-nucleus collisions with high flux up to an invariant mass region hitherto unexplored experimentally. After a general survey photon-photon luminosities in relativistic heavy ion collisions are discussed. Special care is taken to include the effects of strong interactions and nuclear size. Then photon-photon physics at various $\gamma\gamma$ -invariant mass scales is discussed. Invariant masses of up to about 100 GeV can be reached at LHC, and in addition the potential for new physics is available. Photonuclear reactions and other important background effects, mainly diffractive processes are also discussed. Lepton-pair production, especially electron-positron pair production is copious. Due to the strong fields there will be new phenomena, like multiple e^+e^- pair production.

1.2 Introduction

The parton model is very useful to study scattering processes at very high energies. The scattering is described as an incoherent superposition of the scattering of the various constituents. For example, nuclei consist of nucleons which in turn consist of quarks and gluons, photons consist of lepton pairs, electrons consist of photons, etc.. We note that relativistic nuclei have photons as an important constituent, especially for low enough virtuality $Q^2 = -q^2 > 0$ of the photon. This is due to the coherent action of all the charges in the nucleus. The virtuality of the photon is related to the size R of the nucleus by

$$Q^2 \lesssim 1/R^2, \tag{1}$$

the condition for coherence. The radius of a nucleus is given approximately by $R = 1.2 \text{ fm } A^{1/3}$, where A is the nucleon number. From the kinematics of the process one has

$$Q^2 = \frac{\omega^2}{\gamma^2} + q_\perp^2, \quad (2)$$

where ω and q_\perp are energy and transverse momentum of the quasireal photon. This limits the maximum energy of the quasireal photon to

$$\omega < \omega_{max} \approx \frac{\gamma}{R}, \quad (3)$$

where γ is the Lorentz factor of the projectile and the perpendicular component of its momentum to

$$q_\perp \lesssim \frac{1}{R}. \quad (4)$$

We define the ratio $x = \omega/E$, where E denotes the energy of the nucleus $E = M_N \gamma A$ and M_N is the nucleon mass. It is therefore smaller than

$$x < x_{max} = \frac{1}{RM_N A} = \frac{\lambda_C(A)}{R}, \quad (5)$$

where $\lambda_C(A)$ is the Compton wave length of the ion. Here and also throughout the rest of the paper we use natural units, setting $\hbar = c = 1$.

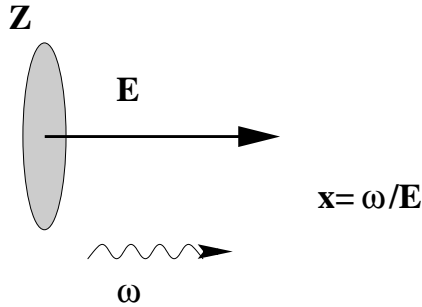


Figure 1: A fast moving nucleus with charge Ze is surrounded by a strong electromagnetic field. This can be viewed as a cloud of virtual photons. These photons can often be considered as real. They are called equivalent or quasireal photons. The ratio of the photon energy ω and the incident ion energy E is denoted by $x = \omega/E$. Its maximal value is restricted by the coherence condition to $x < \lambda_C(A)/R \approx 0.175/A^{4/3}$, that is, $x \lesssim 10^{-3}$ for Ca ions and $x \lesssim 10^{-4}$ for Pb ions.

The collisions of e^+ and e^- has been the traditional way to study $\gamma\gamma$ -collisions. Similarly photon-photon collisions can also be observed in hadron-hadron collisions. Since the photon number scales with Z^2 (Z being the charge number of the nucleus) such effects can be particularly large. Of course, the strong interaction of the two nuclei has to be taken into consideration.

The equivalent photon flux present in medium and high energy nuclear collisions is very high. Recent reviews of the present topic can be found in [7, 8, 9, 10]. This high equivalent photon flux has already found many useful applications in nuclear physics [11], nuclear astrophysics [12, 13], particle physics [14] (sometimes called the “Primakoff effect”), as well as, atomic physics [15]. Here our main purpose is to discuss the physics of photon-photon and photon-hadron (nucleus) collisions in high energy heavy ion collisions. The “Relativistic Heavy Ion Collider” (RHIC), scheduled to begin taking data in 1999, will have a program to investigate such collisions experimentally. The equivalent photon spectrum there extends up to several GeV ($\gamma \approx 100$). Therefore the available invariant mass range is up to about the mass of the η_c . At the recent RHIC/INT (“Institute for Nuclear Theory”) workshop at the LBNL (Berkeley), the physics of peripheral collisions was discussed by S. R. Klein and S. J. Brodsky [16]. When the “Large Hadron Collider” will be scheduled to begin taking data in 2004/2008, the study of these reactions can be extended to both higher luminosities but also to much higher invariant masses, hitherto unexplored.

Relativistic heavy ion collisions have been suggested as a general tool for two photon physics about a decade ago. Yet the study of a special case, the production of e^+e^- pairs in nucleus-nucleus collisions, goes back to the work of Landau and Lifschitz in 1934 [17] (In those days, of course, one thought more about high energy cosmic ray

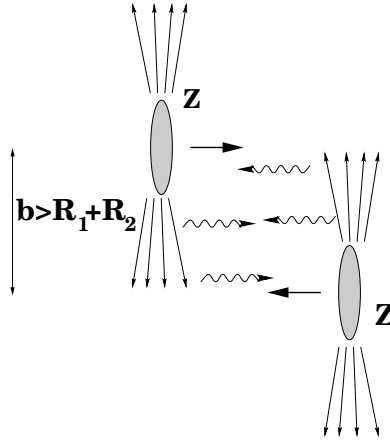


Figure 2: Two fast moving electrically charged objects are an abundant source of (quasireal) photons. They can collide with each other and with the other nucleus. For peripheral collisions with impact parameters $b > 2R$, this is useful for photon-photon as well as photon-nucleus collisions.

nuclei than relativistic heavy ion colliders). The general possibilities and characteristic features of two-photon physics in relativistic heavy ion collisions have been discussed in [18]. The possibility to produce a Higgs boson via $\gamma\gamma$ -fusion was suggested in [19, 20]. In these papers the effect of strong absorption in heavy ion collisions was not taken into account. This absorption is a feature, which is quite different from the two-photon physics at e^+e^- colliders. The problem of taking strong interactions into account was solved by using impact parameter space methods in [21, 22, 23]. Thus the calculation of $\gamma\gamma$ -luminosities in heavy ion collisions is put on a firm basis and rather definite conclusions were reached by many groups working in the field, as described, e.g., in [24, 8, 7]. This opens the way for many interesting applications. Up to now hadron-hadron collisions have not been used for two-photon physics. An exception can be found in [25], where the production of $\mu^+\mu^-$ pairs at the ISR was studied. The special class of events was selected, where no hadrons are seen associated with the muon pair in a large solid angle vertex detector. In this way one makes sure that the hadrons do not interact strongly with each other, i.e., one is dealing with peripheral collisions (with impact parameters $b > 2R$); the photon-photon collisions manifest themselves as “silent events”, that is, with only a small relatively small multiplicity. Dimuons with a very low sum of transverse momenta are also considered as a luminosity monitor for the ATLAS detector at LHC [26].

Experiments are planned at RHIC [2, 3, 4, 5, 6] and are discussed at LHC [27, 28, 29]. We quote J. D. Bjorken [30]: *It is an important portion (of the FELIX program at LHC [31]) to tag on Weizsaecker Williams photons (via the nonobservation of completely undissociated forward ions) in ion-ion running, creating a high luminosity $\gamma\gamma$ collider.*

1.3 From impact-parameter dependent equivalent photon spectra to $\gamma\gamma$ -luminosities

Photon-photon collisions have been studied extensively at e^+e^- colliders. The theoretical framework is reviewed, e.g., in [32]. The basic graph for the two-photon process in ion-ion collisions is shown in Fig. 3. Two virtual (space-like) photons collide to form a final state f . In the equivalent photon approximation (EPA) it is assumed that the square of the 4-momentum of the virtual photons is small, i.e., $q_1^2 \approx q_2^2 \approx 0$ and the photons can be treated as quasireal. In this case the $\gamma\gamma$ -production is factorized into an elementary cross section for the process $\gamma + \gamma \rightarrow f$ (with real photons, i.e., $q^2 = 0$) and a $\gamma\gamma$ -luminosity function. In contrast to the pointlike elementary electrons (positrons), nuclei are extended, strongly interacting objects with internal structure. This gives rise to modifications in the theoretical treatment of two photon processes. The emission of a photon depends on the (elastic) form factor. Often a Gaussian form factor or one of a homogeneous charged sphere is used. The typical behavior of a form factor is

$$f(q^2) \approx \begin{cases} Z & \text{for } |q^2| < \frac{1}{R^2} \\ 0 & \text{for } |q^2| \gg \frac{1}{R^2} \end{cases} . \quad (6)$$

For low $|q^2|$ all the protons inside the nucleus act coherently, whereas for $|q^2| \gg 1/R^2$ the form factor is very small, close to 0. For a medium size nucleus with, say, $R = 5$ fm, the limiting $Q^2 = -q^2 = 1/R^2$ is given by $Q^2 = (40\text{MeV})^2 = 1.6 \times 10^{-3} \text{ GeV}^2$. Apart from e^+e^- (and to a certain extent also $\mu^+\mu^-$) pair production, this scale is much smaller than typical scales in the two-photon processes. Therefore the virtual photons in relativistic heavy ion collisions can be treated as quasireal. This is a limitation as compared to e^+e^- collisions, where the

two-photon processes can also be studied as a function of the corresponding masses q_1^2 and q_2^2 of the exchanged photon (“tagged mode”).

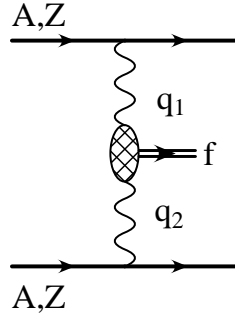


Figure 3: The general Feynman diagram of photon-photon processes in heavy ion collisions: Two (virtual) photons fuse in a charged particle collision into a final system f .

As was discussed already in the previous section, relativistic heavy ions interact strongly when the impact parameter is smaller than the sum of the radii of the two nuclei. In such cases $\gamma\gamma$ -processes are still present and are a background that has to be considered in central collisions. In order to study “clean” photon-photon events however, they have to be eliminated in the calculation of photon-photon luminosities as the particle production due to the strong interaction dominates. In the usual treatment of photon-photon processes in e^+e^- collisions plane waves are used and there is no direct information on the impact parameter. For heavy ion collisions on the other hand it is very appropriate to introduce impact parameter dependent equivalent photon numbers. They have been widely discussed in the literature, see, e.g., [11, 33, 34].

The equivalent photon spectrum corresponding to a point charge Ze , moving with a velocity v at impact parameter b is given by

$$N(\omega, b) = \frac{Z^2\alpha}{\pi^2} \frac{1}{b^2} \left(\frac{c}{v}\right)^2 x^2 \left[K_1^2(x) + \frac{1}{\gamma^2} K_0^2(x) \right], \quad (7)$$

where $K_n(x)$ are the modified Bessel Functions (MacDonald Functions) and $x = \frac{\omega b}{\gamma v}$. Then one obtains the probability for a certain electromagnetic process to occur in terms of the same process generated by an equivalent pulse of light as

$$P(b) = \int \frac{d\omega}{\omega} N(\omega, b) \sigma_\gamma(\omega). \quad (8)$$

Possible modifications of $N(\omega, b)$ due to an extended spherically symmetric charge distribution are given in [35]. It should be noted that Eq. (7) also describes the equivalent photon spectrum of an extended charge distribution, such as a nucleus, as long as b is larger than the extension of the object. This is due to the fact that the electric field of a spherically symmetric system depends only on the total charge, which is inside it.

As the term $x^2 [K_1^2(x) + 1/\gamma^2 K_0^2(x)]$ in Eq. (7) can be roughly approximated as 1 for $x < 1$ and 0 for $x > 1$, that is, the equivalent photon number $N(\omega, b)$ is almost a constant up to a maximum $\omega_{max} = \gamma/b$ ($x = 1$). By integrating the photon spectrum (Eq. (7)) over b from a minimum value of R_{min} up to infinity (where essentially only impact parameter up to $b_{max} \approx \gamma/\omega$ contribute, compare with Eq. (3)), one can define an equivalent photon number $n(\omega)$. This integral can be carried out analytically and is given by [11, 33]

$$n(\omega) = \int d^2b N(\omega, b) = \frac{2}{\pi} Z^2 \alpha \left(\frac{c}{v}\right)^2 \left[\xi K_0 K_1 - \frac{v^2 \xi^2}{2c^2} (K_1^2 - K_0^2) \right], \quad (9)$$

where the argument of the modified Bessel functions is $\xi = \frac{\omega R_{min}}{\gamma v}$. The cross section for a certain electromagnetic process is then

$$\sigma = \int \frac{d\omega}{\omega} n(\omega) \sigma_\gamma(\omega). \quad (10)$$

Using the approximation above for the MacDonald functions, we get an approximated form, which is quite reasonable and is useful for estimates:

$$n(\omega) \approx \frac{2Z^2\alpha}{\pi} \ln \frac{\gamma}{\omega R_{min}} \quad \omega < \gamma/R_{min}. \quad (11)$$

The photon-photon production cross-section is obtained in a similar factorized form, by folding the corresponding equivalent photon spectra of the two colliding heavy ions [22, 23] (for polarization effects see [22], they are neglected here)

$$\sigma_c = \int \frac{d\omega_1}{\omega_1} \int \frac{d\omega_2}{\omega_2} F(\omega_1, \omega_2) \sigma_{\gamma\gamma}(W_{\gamma\gamma}), \quad (12)$$

with

$$F(\omega_1, \omega_2) = 2\pi \int_{R_1}^{\infty} b_1 db_1 \int_{R_2}^{\infty} b_2 db_2 \int_0^{2\pi} d\phi \times N(\omega_1, b_1) N(\omega_2, b_2) \Theta(b_1^2 + b_2^2 - 2b_1 b_2 \cos \phi - R_{cutoff}^2), \quad (13)$$

where $W_{\gamma\gamma} = \sqrt{4\omega_1\omega_2}$ is the invariant mass of the $\gamma\gamma$ -system and $R_{cutoff} = R_1 + R_2$. (In [6] the effect of replacing the simple sharp cutoff (Θ -function) by a more realistic probability of the nucleus to survive is studied. Apart from the very high end of the spectrum, modifications are rather small.) This can also be rewritten in terms of the invariant mass $W_{\gamma\gamma}$ and the rapidity $Y = 1/2 \ln[(P_0 + P_z)/(P_0 - P_z)] = 1/2 \ln(\omega_1/\omega_2)$ as:

$$\sigma_c = \int dW_{\gamma\gamma} dY \frac{d^2 L}{dW_{\gamma\gamma} dY} \sigma_{\gamma\gamma}(W_{\gamma\gamma}), \quad (14)$$

with

$$\frac{d^2 L_{\gamma\gamma}}{dW_{\gamma\gamma} dY} = \frac{2}{W_{\gamma\gamma}} F\left(\frac{W_{\gamma\gamma}}{2} e^Y, \frac{W_{\gamma\gamma}}{2} e^{-Y}\right). \quad (15)$$

Here energy and momentum of the $\gamma\gamma$ -system in the beam direction are denoted by P_0 and P_z . The transverse momentum is of the order of $P_{\perp} \leq 1/R$ and is neglected here. The transverse momentum distribution is calculated in [36].

In [36] and [37] the intuitively plausible formula Eq. (13) is derived ab initio, starting from the assumption that the two ions move on a straight line with impact parameter b . The advantage of heavy nuclei is seen in the coherence factor $Z_1^2 Z_2^2$ contained in the $N(\omega, b)$ in Eq. (13).

As a function of Y , the luminosity $d^2 L/dW_{\gamma\gamma} dY$ for symmetrical ion collisions has a Gaussian shape with the maximum at $Y = 0$. The width is approximately given by $\Delta Y = 2 \ln[(2\gamma)/(RW_{\gamma\gamma})]$, see also Fig. 4. Depending on the experimental situation additional cuts in the allowed Y range are needed.

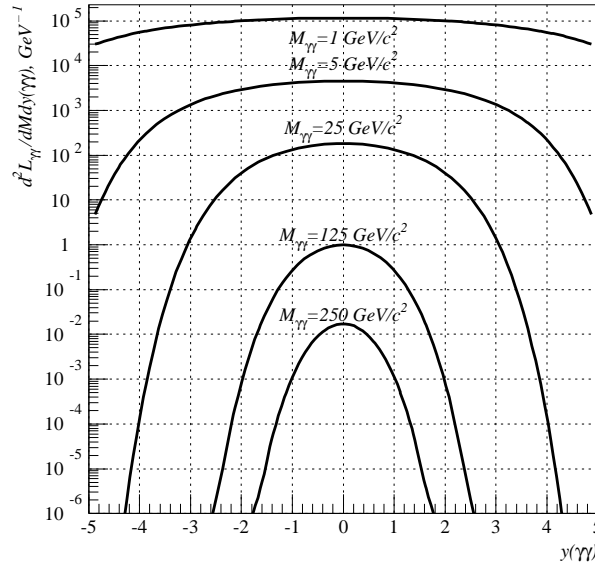


Figure 4: The luminosity function $d^2 L_{\gamma\gamma}/dM dY$ for Pb-Pb collisions with $\gamma = 2950$ as a function of Y for different values of M .

Additional effects due to the nuclear structure have been also studied. For inelastic vertices a photon number $N(\omega, b)$ can also be defined, see, e.g., [7]. Its effect was found to be small. The dominant correction comes from the electromagnetic excitation of one of the ions in addition to the photon emission. We refer to [7] for further details.

In Fig. 5 we give a comparison of effective $\gamma\gamma$ luminosities, that is the product of the beam luminosity with the two-photon luminosity ($L_{AA} \times dL_{\gamma\gamma}/dM$) for various collider scenarios. We use the following collider parameters: LEP200: $E_{el} = 100\text{GeV}$, $L = 10^{32}\text{cm}^{-2}\text{s}^{-1}$, NLC/PLC: $E_{el} = 500\text{GeV}$, $L = 2 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$, Pb-Pb heavy-ion mode at LHC: $\gamma = 2950$, $L = 10^{26}\text{cm}^{-2}\text{s}^{-1}$, Ca-Ca: $\gamma = 3750$, $L = 4 \times 10^{30}\text{cm}^{-2}\text{s}^{-1}$, p-p: $\gamma = 7450$, $L = 10^{30}\text{cm}^{-2}\text{s}^{-1}$. In the Ca-Ca heavy ion mode, higher effective luminosities (defined as collider luminosity times $\gamma\gamma$ -luminosity) can be achieved as, e.g., in the Pb-Pb mode, since higher AA luminosities can be reached there. Since the event rates are proportional to the luminosities, and interesting events are rare (see also below), we think that it is important to aim at rather high luminosities in the ion-ion runs. This should be possible, especially for the medium heavy ions like Ca. For further details see [38, 39, 40].

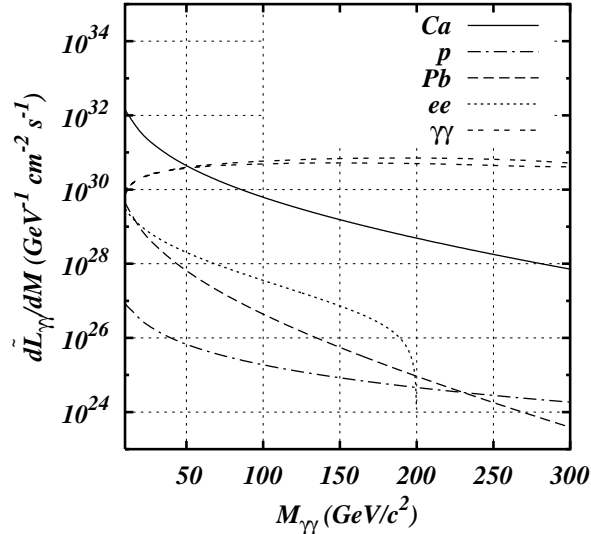


Figure 5: Comparison of the effective $\gamma\gamma$ -Luminosities ($d\tilde{L}_{\gamma\gamma}/dM = L_{AA} \times dL_{\gamma\gamma}/dM$) for different ion species. For comparison the same quantity is shown for LEP200 and a future NLC/PLC (next linear collider/photon linear collider), where photons are obtained by laser backscattering; the results for two different polarizations are shown.

1.4 γ -A interactions

There are many interesting phenomena ranging from the excitation of discrete nuclear states, giant multipole resonances (especially the giant dipole resonance), quasideuteron absorption, nucleon resonance excitation to the nucleon continuum.

The interaction of quasireal photons with protons has been studied extensively at the electron-proton collider HERA (DESY, Hamburg), with $\sqrt{s} = 300\text{ GeV}$ ($E_e = 27.5\text{ GeV}$ and $E_p = 820\text{ GeV}$ in the laboratory system). This is made possible by the large flux of quasi-real photons from the electron (positron) beam. The obtained γp center-of-mass energies (up to $W_{\gamma p} \approx 200\text{ GeV}$) are an order of magnitude larger than those reached by fixed target experiments.

Similar and more detailed studies will be possible at the relativistic heavy ion colliders RHIC and LHC, due to the larger flux of quasireal photons from one of the colliding nuclei. In the photon-nucleon subsystem, one can reach invariant masses $W_{\gamma N}$ up to $W_{\gamma N, max} = \sqrt{4W_{max}E_N} \approx 0.8\gamma A^{-1/6}\text{ GeV}$. For Pb at LHC ($\gamma = 2950$) one obtains 950 GeV and even higher values for Ca. Thus one can study physics quite similar to the one at HERA, with nuclei instead of protons. Photon-nucleon physics includes many aspects, like the energy dependence of total cross-sections, diffractive and non-diffractive processes.

An important subject is the elastic vector meson production $\gamma p \rightarrow Vp$ (with $V = \rho, \omega, \phi, J/\Psi, \dots$). A review of exclusive neutral vector meson production is given in [41]. The diffractive production of vector mesons allows one to get insight into the interface between perturbative QCD and hadronic physics. Elastic processes (i.e., the proton remains in the ground state) have to be described within nonperturbative (and therefore phenomenological) models. It was shown in [42] that diffractive (“elastic”) J/Ψ photoproduction is a probe of the gluon density at $x \approx \frac{M_V^2}{W_{\gamma N}^2}$ (for quasireal photons). Inelastic J/Ψ photoproduction was also studied recently at HERA [43].

Going to the hard exclusive photoproduction of heavy mesons on the other hand, perturbative QCD is applicable.

Recent data from HERA on the photoproduction of J/Ψ mesons have shown a rapid increase of the total cross section with $W_{\gamma N}$, as predicted by perturbative QCD. Such studies could be extended to photon-nucleus interactions at RHIC, thus complementing the HERA studies. Equivalent photon flux factors are large for the heavy ions due to coherence. On the other hand, the A-A luminosities are quite low, as compared to HERA. Of special interest is the coupling of the photon of one nucleus to the Pomeron-field of the other nucleus. Such studies are envisaged for RHIC, see [2, 3, 4, 5] where also experimental feasibility studies were performed.

Estimates of the order of magnitude of vector meson production in photon-nucleon processes at RHIC and LHC are given in [7]. In AA collisions there is incoherent photoproduction on the individual A nucleons. Shadowing effects will occur in the nuclear environment and it will be interesting to study these [44]. There is also the coherent contribution where the nucleus remains in the ground state. Due to the large momentum transfer, the total (angle integrated) coherent scattering shows an $A^{4/3}$ dependence. (It will be interesting to study shadow effects in this case also). This is in contrast to, e.g., low energy νA elastic scattering, where the coherence effect leads to an A^2 dependence. For a general pedagogical discussion of the coherence effects see, e.g., [45]. The coherent exclusive vector meson production at RHIC was studied recently in [46]. The increase of the cross section with A was found there to be between the two extremes ($A^{4/3}$ and A^2) mentioned above. In this context, RHIC and LHC can be considered as vector meson factories [46]. In addition there are inelastic contributions, where the proton (nucleon) is transformed into some final state X during the interaction (see [43]).

At the LHC one can extend these processes to much higher invariant masses W , therefore much smaller values of x will be probed. Whereas the J/Ψ production at HERA was measured up to invariant masses of $W \approx 160$ GeV, the energies at the LHC allow for studies up to ≈ 1 TeV.

At the LHC [31] hard diffractive vector meson photoproduction can be investigated especially well in AA collisions. In comparison to previous experiments, the very large photon luminosity should allow observation of processes with quite small γp cross sections, such as Υ -production. For more details see [31].

Photo-induced processes are also of practical importance as they are a serious source of beam loss as they lead in general to a change of the charge-to-mass ratio of the nuclei. Especially the cross section for the excitation of the giant dipole resonance, a collective mode of the nucleus, is rather large for the heavy systems (of the order of 100b). The cross section scales approximately with $Z^{10/3}$. The contribution nucleon resonances (especially the Δ resonance) has also been confirmed experimentally in fixed target experiments with 60 and 200 GeV/A (heavy ions at CERN, “electromagnetic spallation”) [47, 48, 49]. For details of these aspects, we refer the reader to [8, 50, 51, 52], where scaling laws, as well as detailed calculations for individual cases are given.

1.5 Photon-Photon Physics at various invariant mass scales

Up to now photon-photon scattering has been mainly studied at e^+e^- colliders. Many reviews [32, 53, 54] as well as conference reports [55, 56, 57, 58, 59] exist. The traditional range of invariant masses has been the region of mesons, ranging from π^0 ($m_{\pi^0} = 135$ MeV) up to about η_c ($m_{\eta_c} = 2980$ MeV). Recently the total $\gamma\gamma \rightarrow$ hadron cross-section has been studied at LEP2 up to an invariant mass range of about 70 GeV [60]. We are concerned here mainly with the invariant mass region relevant for LHC (see the $\gamma\gamma$ -luminosity figures below). Apart from the production of e^+e^- (and $\mu^+\mu^-$) pairs, the photons can always be considered as quasireal. The cross section for virtual photons deviates from the one for real photons only for Q^2 , which are much larger than the coherence limit $Q^2 \lesssim 1/R^2$ (see also the discussion in [32]). For real photons general symmetry requirements restrict the possible final states, as is well known from the Landau-Yang theorem. Especially it is impossible to produce spin 1 final states. In e^+e^- annihilation only states with $J^{PC} = 1^{--}$ can be produced directly. Two photon collisions give access to most of the $C = +1$ mesons.

In principle $C = -1$ vector mesons can be produced by the fusion of three (or, less important, five, seven, ...) equivalent photons. This cross section scales with Z^6 . But it is smaller than the contribution coming from γ -A collisions, as discussed above, even for nuclei with large Z (see [7]).

The cross section for $\gamma\gamma$ -production in a heavy ion collision factorizes into a $\gamma\gamma$ -luminosity function and a cross-section $\sigma_{\gamma\gamma}(W_{\gamma\gamma})$ for the reaction of the (quasi)real photons $\gamma\gamma \rightarrow f$, where f is any final state of interest (see Eq. (12)). When the final state is a narrow resonance, the cross-section for its production in two-photon collisions is given by

$$\sigma_{\gamma\gamma \rightarrow R}(M^2) = 8\pi^2(2J_R + 1)\Gamma_{\gamma\gamma}(R)\delta(M^2 - M_R^2)/M_R, \quad (16)$$

where J_R , M_R and $\Gamma_{\gamma\gamma}(R)$ are the spin, mass and two-photon width of the resonance R . This makes it easy to calculate the production cross-section $\sigma_{AA \rightarrow AA+R}$ of a particle in terms of its basic properties.

In Fig. 6 the function $4\pi^2 dL_{\gamma\gamma}/dM/M^2$, which is universal for a produced resonances, is plotted for various systems. It can be directly used to calculate the cross-section for the production of a resonance R with the formula

$$\sigma_{AA \rightarrow AA+R}(M) = (2J_R + 1)\Gamma_{\gamma\gamma} \frac{4\pi^2 dL_{\gamma\gamma}/dM}{M^2}. \quad (17)$$

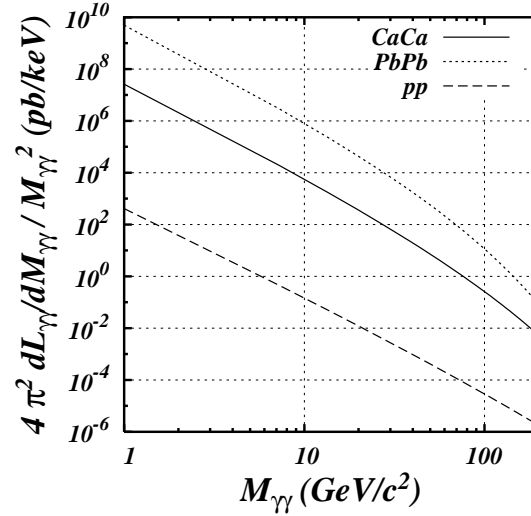


Figure 6: The universal function $4\pi^2 dL_{\gamma\gamma}/dM_{\gamma\gamma}/M_{\gamma\gamma}^2$ is plotted for different ion species at LHC. We use $R = 1.2A^{1/3} \text{ fm}$ and $\gamma = 2950, 3750$ and 7000 for Pb-Pb, Ca-Ca and p-p, respectively.

We will now give a general discussion of possible photon-photon physics at relativistic heavy ion colliders. Invariant masses up to several GeV can be reached at RHIC and up to about 100 GeV at LHC.

We can divide our discussion into the following two main subsections: Basic QCD phenomena in $\gamma\gamma$ -collisions (covering the range of meson, meson-pair production, etc.) and $\gamma\gamma$ -collisions as a tool for new physics, especially at very high invariant masses. An interesting topic in itself is the e^+e^- pair production. The fields are strong enough to produce multiple pairs in a single collisions. A discussion of this subject together with calculations within the semiclassical approximation can be found in [61, 62, 63, 64]

1.6 Basic QCD phenomena in $\gamma\gamma$ -collisions

1.6.1 Hadron spectroscopy: Light and heavy quark spectroscopy

One may say that photon-photon collisions provide an independent view of the meson and baryon spectroscopy. They provide powerful information on both the flavor and spin/angular momentum internal structure of the mesons. Much has already been done at e^+e^- colliders. Light quark spectroscopy is very well possible at RHIC, benefiting from the high $\gamma\gamma$ -luminosities. Detailed feasibility studies exist [2, 3, 4, 5]. In these studies, $\gamma\gamma$ signals and backgrounds from grazing nuclear and beam gas collisions were simulated with both the FRITIOF and VENUS Monte Carlo codes. The narrow p_\perp -spectra of the $\gamma\gamma$ -signals provide a good discrimination against the background, see also the discussion of a possible trigger in 1.10 below. The possibilities to produce these mesons at the LHC have been discussed in detail in the FELIX LoI [31]. Also discussed there are how to isolate $\gamma\gamma$ events in ion-ion collisions and applications to basic QCD phenomena like $C = +1$ meson production, vector meson pair production and total hadronic $\gamma\gamma$ cross sections. Rates are given and possible triggers are discussed. In addition photon-Pomeron and Pomeron-Pomeron processes are discussed. The general conclusion is that all these processes are very promising tools for vector meson spectroscopy.

In particular the absence of meson production via $\gamma\gamma$ -fusion is also of great interest for glueball search. The two-photon width of a resonance is a probe of the charge of its constituents, so the magnitude of the two-photon coupling can serve to distinguish quark dominated resonances from glue-dominated resonances (“glueballs”). In $\gamma\gamma$ -collisions, a glueball can only be produced via the annihilation of a $q\bar{q}$ pair into a pair of gluons, whereas a normal $q\bar{q}$ -meson can be produced directly. Therefore we expect the ratio for the production of a glueball G

compared to a normal $q\bar{q}$ meson M to be

$$\frac{\sigma(\gamma\gamma \rightarrow M)}{\sigma(\gamma\gamma \rightarrow G)} = \frac{\Gamma(M \rightarrow \gamma\gamma)}{\Gamma(G \rightarrow \gamma\gamma)} \sim \frac{1}{\alpha_s^2}, \quad (18)$$

where α_s is the strong interaction coupling constant. On the other hand glueballs are most easily produced in a glue-rich environment, for example, in radiative J/Ψ decays, $J/\Psi \rightarrow \gamma gg$. In this process we expect the ratio of the cross section to be

$$\frac{\Gamma(J/\Psi \rightarrow \gamma G)}{\Gamma(J/\Psi \rightarrow \gamma M)} \sim \frac{1}{\alpha_s^2}. \quad (19)$$

A useful quantity to describe the gluonic character of a mesonic state X is therefore the so called “stickiness” [65], defined as

$$S_X = \frac{\Gamma(J/\Psi \rightarrow \gamma X)}{\Gamma(X \rightarrow \gamma\gamma)}. \quad (20)$$

One expects the stickiness of all mesons to be comparable, while for glueballs it should be enhanced by a factor of about $1/\alpha_s^4 \sim 20$. In a recent reference [66] results of the search for $f_J(2220)$ production in two-photon interactions were presented. There a very small upper limit for the product of $\Gamma_{\gamma\gamma} B_{K_s K_s}$ was given, where $B_{K_s K_s}$ denotes the branching fraction of its decay into $K_s K_s$. From this it was concluded that this is a strong evidence that the $f_J(2220)$ is a glueball.

For charmonium production, the two-photon width $\Gamma_{\gamma\gamma}$ of η_c (2960 MeV, $J^{PC} = 0^{-+}$) is known from experiment [67]. But the two-photon widths of P -wave charmonium states have been measured with only modest accuracy. Two photon widths of P -wave charmonium states can be estimated following the PQCD approach [68]. Similar predictions of the bottomonia two photons widths can be found in [69, 70]. For RHIC the study of η_c is a real challenge [3]; the luminosities are falling and the branching ratios to experimentally interesting channels are small.

In Table 1 (adapted from table 2.6 of [31]) the two-photon production cross-sections for $c\bar{c}$ and $b\bar{b}$ mesons in the rapidity range $|Y| < 7$ are given. Also given are the number of events in a 10^7 sec run with the ion luminosities of $4 \times 10^{30} \text{cm}^{-2} \text{s}^{-1}$ for Ca-Ca and $10^{26} \text{cm}^{-2} \text{s}^{-1}$ for Pb-Pb. Millions of C -even charmonium states will be produced in coherent two-photon processes during a standard 10^7 sec heavy ion run at the LHC. The detection efficiency of charmonium events has been estimated as 5% for the forward-backward FELIX geometry [31], i.e., one can expect detection of about 5×10^3 charmonium events in Pb-Pb and about 10^6 events in Ca-Ca collisions. This is two to three orders of magnitude higher than what is expected during five years of LEP200 operation. Experiments with a well-equipped central detector like CMS on the other hand should provide a much better efficiency. Further details, also on experimental cuts, backgrounds and the possibilities for the study of C -even bottomonium states are given in [31].

State	Mass, MeV	$\Gamma_{\gamma\gamma}$ keV	$\sigma(AA \rightarrow AA + X)$		rates per 10^7 sec	
			Pb-Pb	Ca-Ca	Pb-Pb	Ca-Ca
π_0	134	8×10^{-3}	46 mbarn	210 μbarn	4.6×10^7	8.4×10^9
η	547	0.46	20 mbarn	100 μbarn	2×10^7	4.0×10^9
η'	958	4.2	25 mbarn	130 μbarn	2.5×10^7	5.2×10^9
$f_2(1270)$	1275	2.4	25 mbarn	133 μbarn	2.5×10^7	5.2×10^9
$a_2(1320)$	1318	1.0	9.2 mbarn	49 μbarn	9.2×10^6	2.0×10^9
$f_2'(1525)$	1525	0.1	540 μbarn	2.9 μbarn	5.4×10^5	1.2×10^8
η_c	2981	7.5	360 μbarn	2.1 μbarn	3.6×10^5	8.4×10^7
χ_{0c}	3415	3.3	180 μbarn	1.0 μbarn	1.8×10^5	4.0×10^7
χ_{2c}	3556	0.8	74 μbarn	0.44 μbarn	7.4×10^4	1.8×10^7
η_b	9366	0.43	450 nbarn	3.1 nbarn	450	1.2×10^4
η_{0b}	9860	2.5×10^{-2}	21 nbarn	0.15 nbarn	21	6000
η_{2b}	9913	6.7×10^{-3}	28 nbarn	0.20 nbarn	28	8000

Table 1: Mass, and $\gamma\gamma$ -widths used to calculate the cross section for meson production for Pb-Pb and Ca-Ca collisions at CMS. Masses and widths are taken from [67] and [31]. The beam luminosities used are $10^{26} \text{cm}^{-2} \text{s}^{-1}$ for Pb-Pb and $4 \times 10^{30} \text{cm}^{-2} \text{s}^{-1}$ for Ca-Ca.

1.6.2 Vector-meson pair production. Total hadronic cross-section

There are various mechanisms to produce hadrons in photon-photon collisions. Photons can interact as point particles which produce quark-antiquark pairs (jets), which subsequently hadronize. Often a quantum fluctuation

transforms the photon into a vector meson ($\rho, \omega, \phi, \dots$) (VMD component) opening up all the possibilities of hadronic interactions. In hard scattering, the structure of the photon can be resolved into quarks and gluons. Leaving a spectator jet, the quarks and gluon contained in the photon will take part in the interaction. It is of great interest to study the relative amounts of these components and their properties.

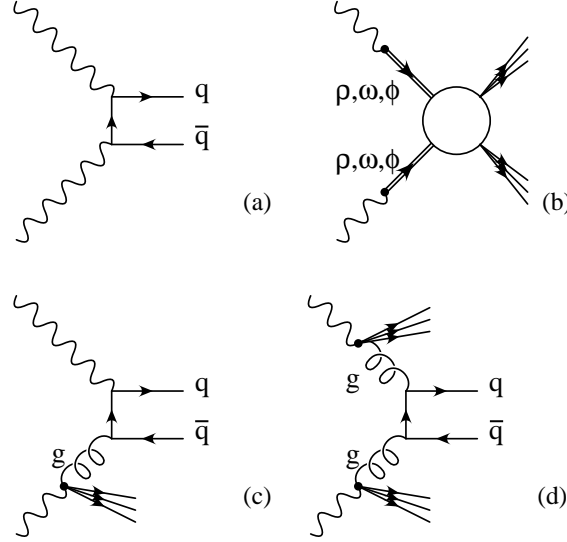


Figure 7: Diagrams showing the contribution to the $\gamma\gamma \rightarrow \text{hadron}$ reaction: direct mechanism (a), vector meson dominance (b), single (c) and double (d) resolved photons.

The L3 collaboration recently made a measurement of the total hadron cross-section for photon-photon collisions in the interval $5\text{GeV} < W_{\gamma\gamma} < 75\text{GeV}$ [60]. It was found that the $\gamma\gamma \rightarrow \text{hadrons}$ cross-section is consistent with the universal Regge behavior of total hadronic cross-sections. The production of vector meson pairs can well be studied at RHIC with high statistics in the GeV region [2]. For the possibilities at LHC, we refer the reader to [31] and [29], where also experimental details and simulations are described.

1.7 $\gamma\gamma$ -collisions as a tool for new physics

The high flux of photons at relativistic heavy ion colliders offers possibilities for the search of new physics. This includes the discovery of the Higgs-boson in the $\gamma\gamma$ -production channel or new physics beyond the standard model, like supersymmetry or compositeness.

Let us mention here the plans to build an e^+e^- linear collider. Such future linear colliders will be used for e^+e^- , $e\gamma$ and $\gamma\gamma$ -collisions (PLC, photon linear collider). The photons will be obtained by scattering of laser photons (of eV energy) on high energy electrons ($\approx \text{TeV}$ region) (see [71]). Such photons in the TeV energy range will be monochromatic and polarized. The physics program at such future machines is discussed in [72], it includes Higgs boson and gauge boson physics and the discovery of new particles.

While the $\gamma\gamma$ invariant masses which will be reached at RHIC will mainly be useful to explore QCD at lower energies, the $\gamma\gamma$ invariant mass range at LHC — up to about 100 GeV — will open up new possibilities.

A number of calculations have been made for a medium heavy standard model Higgs [73, 74, 75, 76]. For masses $m_H < 2m_{W^\pm}$ the Higgs bosons decays dominantly into $b\bar{b}$. Chances of finding the standard model Higgs in this case are marginal [29].

An alternative scenario with a light Higgs boson was, e.g., given in [77] in the framework of the “general two Higgs doublet model”. Such a model allows for a very light particle in the few GeV region. With a mass of 10 GeV, the $\gamma\gamma$ -width is about 0.1 keV. The authors of [77] proposed to look for such a light neutral Higgs boson at the proposed low energy $\gamma\gamma$ -collider. We want to point out that the LHC Ca-Ca heavy ion mode would also be very suitable for such a search.

One can also speculate about new particles with strong coupling to the $\gamma\gamma$ -channel. Large $\Gamma_{\gamma\gamma}$ -widths will directly lead to large $\gamma\gamma$ production cross-sections. We quote the papers [78, 79]. Since the $\gamma\gamma$ -width of a resonance is

mainly proportional to the wave function at the origin, huge values can be obtained for very tightly bound systems. Composite scalar bosons at $W_{\gamma\gamma} \approx 50$ GeV are expected to have $\gamma\gamma$ -widths of several MeV [78, 79]. The search for such kind of resonances in the $\gamma\gamma$ -production channel will be possible at LHC.

In Refs. [80, 81] $\gamma\gamma$ -processes at pp colliders (LHC) are studied. It is observed there that non-strongly interacting supersymmetric particles (sleptons, charginos, neutralinos, and charged Higgs bosons) are difficult to detect in hadronic collisions at the LHC. The Drell-Yan and gg -fusion mechanisms yield low production rates for such particles. Therefore the possibility of producing such particles in $\gamma\gamma$ interactions at hadron colliders is examined. Since photons can be emitted from protons which do not break up in the radiation process, clean events can be generated which should compensate for the small number. In [80] it was pointed out that at the high luminosity of $L = 10^{34} \text{cm}^{-2} \text{s}^{-1}$ at the LHC(pp), one expects about 16 minimum bias events per bunch crossing. Even the elastic $\gamma\gamma$ events will therefore not be free of hadronic debris. Clean elastic events will be detectable at luminosities below $10^{33} \text{cm}^{-2} \text{s}^{-1}$. This danger of “overlapping events” has also to be checked for the heavy ion runs, but it will be much reduced due to the lower luminosities. Recent (unpublished) studies done for FELIX and ALICE show that the chargino pair production can be detectable, if the lightest chargino would have a mass below $60 \text{ GeV}/c^2$. Unfortunately recent chargino mass limits set by LEP experiments already exclude the existence of charginos on this mass range. Therefore the observation of MSSM-particles in $\gamma\gamma$ -interactions in heavy ion collisions seems to be hard to achieve.

Similar considerations for new physics were also made in connection with the planned eA collider at DESY (Hamburg). Again, the coherent field of a nucleus gives rise to a Z^2 factor in the cross-section for photon-photon processes in eA collisions [82].

1.8 Dilepton production

Electrons (positrons) and to some extent also muons have a special status, which is due to their small mass. They are therefore produced more easily than other heavier particles and in the case of e^+e^- pair production also lead to new phenomena, like multiple pair production. Due to their small mass and therefore large Compton wave length (compared to the nuclear radius), the equivalent photon approximation has to be modified when applied to them. For the muon, with a Compton wavelength of about 2 fm, we expect the standard equivalent photon approximation to be applicable, with only small corrections. Both electrons and muons can be produced not only as free particles but also into an atomic states bound to one of the ions, or even as a bound state, positronium or muonium.

The special situation of the electron pairs can already be seen from the formula for the impact parameter dependent probability in lowest order. Using the equivalent photon approximation one obtains [11]

$$P^{(1)}(b) \approx \frac{14}{9\pi^2} (Z\alpha)^4 \frac{1}{m_e^2 b^2} \ln^2 \left(\frac{\gamma_{ion} \delta}{2m_e b} \right), \quad (21)$$

where $\delta \approx 0.681$ and $\gamma_{ion} = 2\gamma^2 - 1$ the Lorentz factor in the target frame, one can see that at RHIC and LHC energies and for impact parameters of the order of the Compton wave length $b \approx 1/m_e$, this probability exceeds one. Unitarity is restored by considering the production of multiple pairs [61, 83, 84, 85, 62]. To a good approximation the multiple pair production can be described by a Poisson distribution. The impact parameter dependent probability needed in this Poisson distribution was calculated in lowest order in [63, 86], the total cross section for the one-pair production in [87], for one and multiple pair production in [64]. Of course the total cross section is dominated by the single pair production as the main contribution to the cross section comes from very large impact parameters b . On the other hand one can see that for impact parameters b of about $2R$ the number of electron-positron pairs produced in each ion collision is about 5 (2) for LHC with $Z = 82$ (RHIC with $Z = 79$). This means that each photon-photon event — especially those at a high invariant mass — which occur predominantly at impact parameters close to $b \gtrsim 2R$ — is accompanied by the production of several (low-energy) e^+e^- pairs.

As the total cross section for this process is huge (about 200 kbarn for Pb-Pb at LHC), one has to take this process into account as a possible background process. Most of the particles are produced at low invariant masses (below 10 MeV) and into the very forward direction (see Fig. 9). High energetic electrons and positrons are even more concentrated along the beam pipe, most of them therefore are unobserved. On the other hand, a substantial amount of them is still left at high energies, e.g., above 1 GeV. These QED pairs therefore constitute a potential hazard for the detectors, see below in Sec. 1.10. On the other hand, they can also be useful as a possible luminosity monitor, as discussed in [31, 26].

Differential production probabilities for $\gamma\gamma$ -dileptons in central relativistic heavy ion collisions are calculated using

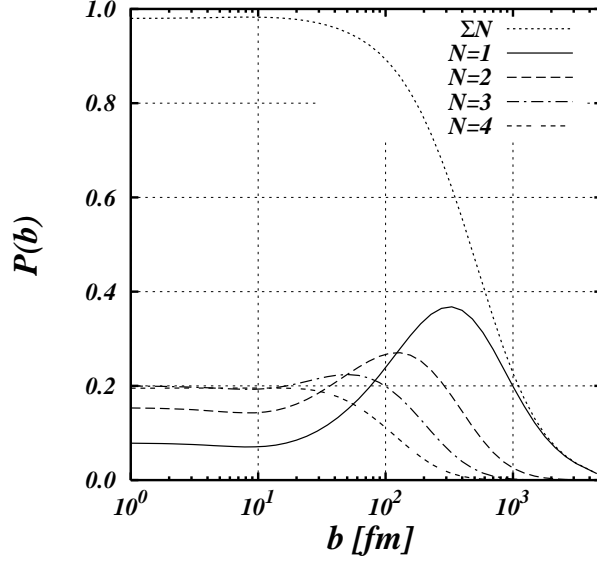


Figure 8: The impact parameter dependent probability to produce N e^+e^- -pairs ($N = 1, 2, 3, 4$) in one collision is shown for the LHC ($\gamma = 2950, \text{Pb-Pb}$). Also shown is the total probability to produce at least one e^+e^- -pair. One sees that at small impact parameters multiple pair production dominates over single pair production.

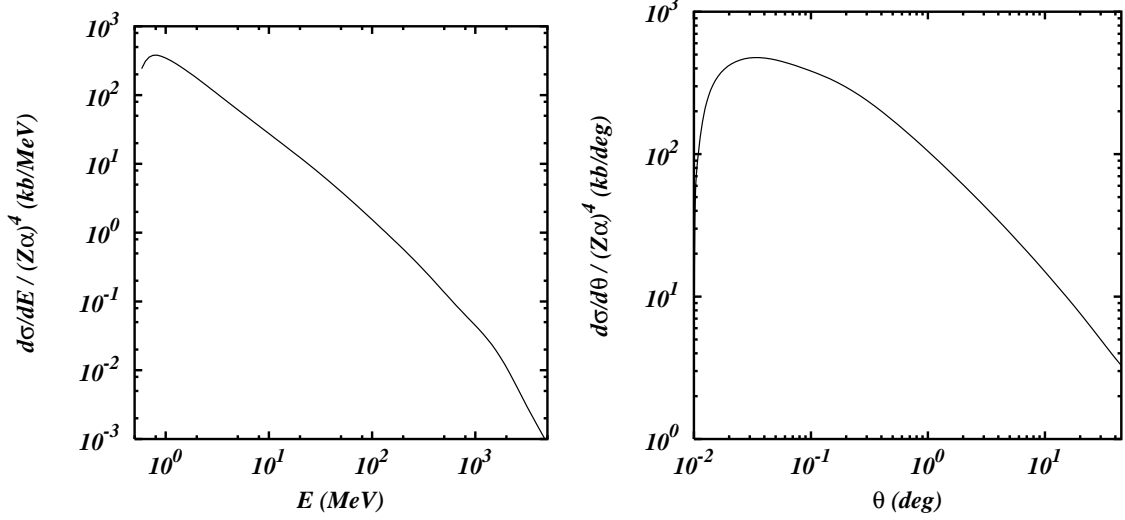


Figure 9: Cross section for the e^+e^- pair production as a function of the energy (A) of either electron or positron and as a function of the angle of the electron or positron with the beam axis (B). Most pairs are produced with energies between 2–5 MeV and in the very forward or backward direction.

the equivalent photon approximation and an impact parameter formulation and compared to Drell-Yan and thermal ones in [37, 88, 89]. The very low p_\perp values and the angular distribution of the pairs give a handle for their discrimination.

Higher order corrections, e.g., Coulomb corrections, have to be taken into account for certain regions in the phase space. A classical result for these higher-order effects can be found in the Bethe-Heitler formula for the process $Z + \gamma \rightarrow Z + e^+ + e^-$

$$\sigma = \frac{28}{9} Z^2 \alpha_e^2 \left[\ln \frac{2\omega}{m_e} - \frac{109}{42} - f(Z\alpha) \right], \quad (22)$$

with the higher-order term given by

$$f(Z\alpha) = (Z\alpha)^2 \sum_{n=1}^{\infty} \frac{1}{n(n^2 + (Z\alpha)^2)} \quad (23)$$

and $r_e = \alpha/m_e$ is the classical electron radius. As far as total cross sections are concerned the higher-order contributions tends to a constant for $\omega \rightarrow \infty$. A systematic way to take leading terms of higher order effects into account in e^+e^- pair production is pursued in [90, 91] using Sudakov variables and the impact-factor representation. They find a reduction of the single-pair production cross section of the order of 10%. In contrast to this some papers have recently discussed nonperturbative results using a light-cone approach [92, 93, 94]. There it is found that the single-pair production cross section is identical to the lowest order result. A calculation of the change of multiple pair production cross section due to such higher order effects can be found in [95].

1.8.1 Equivalent Muons

Up to now only the production of dileptons was considered, for which the four-momentum Q^2 of the photons was less than about $1/R^2$ (coherent interactions). There is another class of processes, where one of the interactions is coherent ($Q^2 \leq 1/R^2$) and the other one involves a deep inelastic interaction ($Q^2 \gg 1/R^2$), see Fig. 10. These processes are readily described using the equivalent electron– (or muon–, or tau–) approximation, as given, e.g., in [96, 97]. The equivalent photon can be considered as containing muons as partons, that is, consisting in part of an equivalent muon beam. The equivalent muon number is given by [96]

$$f_{\mu/\gamma}(\omega, x) = \frac{\alpha}{\pi} \ln \left(\frac{\omega}{m_\mu} \right) (x^2 + (1-x)^2), \quad (24)$$

where m_μ denotes the muon mass. The muon energy E_μ is given by $E_\mu = x\omega$, where ω is the energy of the equivalent photon. This spectrum has to be folded with the equivalent photon spectrum given by

$$f_{\gamma/Z}(u) = \frac{2\alpha}{\pi} \frac{Z^2}{u} \ln \left(\frac{1}{um_A R} \right) \quad (25)$$

for $u < u_{max} = \frac{1}{Rm_A}$. The deep inelastic lepton-nucleon scattering can now be calculated in terms of the structure functions F_1 and F_2 of the nucleon. The inclusive cross section for the deep-inelastic scattering of the equivalent muons is therefore given by

$$\frac{d^2\sigma}{dE'd\Omega} = \int dx_1 f_{\mu/Z}(x_1) \frac{d^2\sigma}{dE'd\Omega}(x_1) \quad (26)$$

where $\frac{d^2\sigma}{dE'd\Omega}(x_1)$ can be calculated from the usual invariant variables in deep inelastic lepton scattering (see, e.g., Eq. 35.2 of [98]). The lepton is scattered to an angle θ with an energy E' . The equivalent muon spectrum of the heavy ion is obtained as

$$f_{\mu/Z}(x_1) = \int_{x_1}^{u_{max}} du f_{\gamma/Z}(u) f_{\mu/\gamma}(x_1/u). \quad (27)$$

This expression can be calculated analytically and work on this is in progress [99].

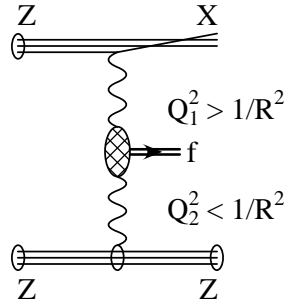


Figure 10: With $Q^2 < 1/R^2$ the photon is emitted coherently from all “partons” inside the ion. For $Q^2 \gg 1/R^2$ the “partonic” structure of the ion is resolved.

Such events are characterized by a single muon with an energy E' and scattering angle θ . The accompanying muon of opposite charge, as well as the remnants of the struck nucleus, will scatter to small angles and remain unobserved. The hadrons scattered to large angles can be observed, with total energy E_h and momentum in the beam direction of p_{zh} . Using the Jacquet-Blondel variable y_{JB} the energy of the equivalent muon can in principle be reconstructed as

$$E_\mu = \frac{1}{2} (E_h - p_{zh} + E'(1 - \cos \theta)) \quad (28)$$

This is quite similar to the situation at HERA, with the difference that the energy of the lepton beam is continuous, and its energy has to be reconstructed from the kinematics (How well this can be done in practice remains to be seen).

1.8.2 Radiation from e^+e^- pairs

The bremsstrahlung in peripheral relativistic heavy ion collisions was found to be small, both for real [11] and virtual [100] bremsstrahlung photons. This is due to the large mass of the heavy ions. Since the cross section for e^+e^- pair production is so large, one can expect to see sizeable effects from the radiation of these light mass particles. In the soft photon limit (see, e.g., [101]) one can calculate the cross section for soft photon emission of the process as

$$Z + Z \rightarrow Z + Z + e^+ + e^- + \gamma \quad (29)$$

as

$$d\sigma(k, p_-, p_+) = -e^2 \left[\frac{p_-}{p_- \cdot k} - \frac{p_+}{p_+ \cdot k} \right]^2 \frac{d^3k}{4\pi^2\omega} d\sigma_0(p_+, p_-) \quad (30)$$

where $d\sigma_0$ denotes the cross section for the e^+e^- pair production in heavy ion collisions. An alternative approach is done by using the equivalent photon approximation (EPA) and calculating the exact lowest order matrix element for the process

$$\gamma + \gamma \rightarrow e^+ + e^- + \gamma.$$

In Fig. 11 we show results of calculations for low energy photons. For this we have used the exact lowest order QED process in the equivalent photon approximation [102].

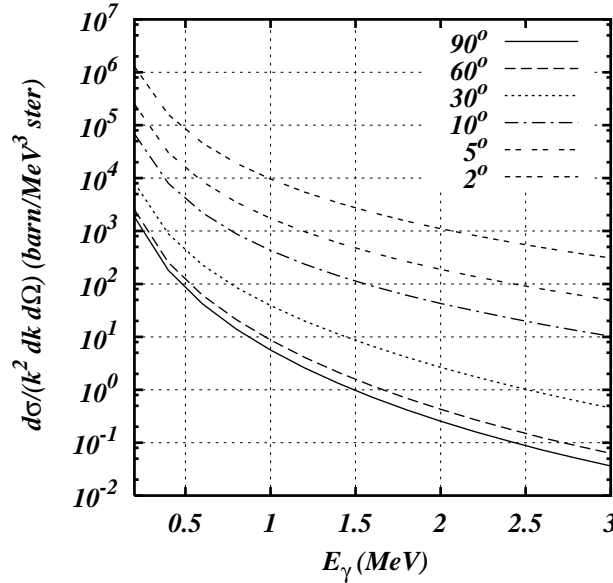


Figure 11: The energy-dependence of bremsstrahlung-photon production from e^+e^- pair production is shown for different angles. We show results for Pb-Pb collisions at LHC.

These low energy photons might constitute a background for the detectors. Unlike the low energy electrons and positrons, they are of course not bent away by the magnets. The angular distribution of the photons also peak at small angles, but again a substantial amount is still left at larger angles, even at 90° . The typical energy of these low energy photons is of the order of several MeV, i. e., much smaller than the expected level of the energy equivalent noise in the CMS ECALs [103].

1.8.3 Bound-free Pair Production

The bound-free pair production, also known as electron-pair production with capture, is a process, which is also of practical importance in the collider. It is the process, where a pair is produced but with the electron not as a free particle, but into an atomic bound state of one of the nuclei. As this changes the charge state of the nucleus, it is

lost from the beam. Together with the electromagnetic dissociation of the nuclei (see Sec. 1.4) these two processes are the dominant loss processes for heavy ion colliders.

In [11] an approximate value for this cross section is given as

$$\sigma_{capt}^K \approx \frac{33\pi}{10} Z_1^2 Z_2^6 \alpha^6 r_e^2 \frac{1}{\exp(2\pi Z_2 \alpha) - 1} \left[\ln(\gamma_{ion} \delta/2) - \frac{5}{3} \right], \quad (31)$$

where $\gamma_{ion} = 2\gamma^2 - 1$ is the Lorentz factor of the ion in the rest frame of the other ion and only capture to the K -shell is included. The cross section for all higher shells is expected to be of the order of 20% of this cross section (see Eqs 7.6.23 and 24 of [11]).

The cross section in Eq. (31) is of the form

$$\sigma = C \ln \gamma_{ion} + D. \quad (32)$$

This form has been found to be a universal one at sufficient high values of γ . The constant C and D then only depend on the type of the target.

The above cross section was found making use of the equivalent photon approximation (EPA) and also using approximate wave function for bound state and continuum. More precise calculations exist [104, 105, 106, 107, 108, 109] in the literature. Recent calculations within DWBA for high values of γ have shown that the exact first order results do not differ significantly from EPA results [110, 111]. Parameterizations for C and D [105, 107] for typical cases are given in Table 2.

Ion	C	D	$\sigma(\gamma = 106)$	$\sigma(\gamma = 2950)$
Pb	15.4barn	−39.0barn	115 barn	222 barn
Au	12.1barn	−30.7barn	90 barn	173 barn
Ca	1.95mbarn	−5.19mbarn	14 mbarn	27.8 mbarn
O	4.50 μ barn	−12.0 μ barn	32 μ barn	64.3 μ barn

Table 2: Parameters C and D (see Eq. (32)) as well as total cross sections for the bound-free pair production for RHIC and LHC. The parameters are taken from [107].

For a long time the effect of higher order and nonperturbative processes have been under investigation. At lower beam energies, in the region of few GeV per nucleon, coupled channel calculations have indicated for a long time, that these give large contributions, especially at small impact parameters. Newer calculation tend to predict considerably smaller values, of the order of the first order result and in a recent article Baltz [112] finds in the limit $\gamma \rightarrow \infty$ that contributions from higher orders are even slightly smaller than the first order results.

The bound-free pair production was measured in two recent experiments at the SPS, at fixed target $\gamma = 168$ [113] and at fixed target $\gamma \approx 2$ [114, 115]. Both experiments found good agreement between measurement and calculations.

We note that electron and positron can also form a bound state, positronium. This is in analogy to the $\gamma\gamma$ -production of mesons ($q\bar{q}$ states) discussed in Sec. 1.5. With the known width of the parapositronium $\Gamma((e^+e^-)_{n=1}^1 S_0 \rightarrow \gamma\gamma) = mc^2\alpha^5/2$, the photon-photon production of this bound state was calculated in [116]. The production of orthopositronium, $n = 1^3 S_1$ was calculated recently [117].

As discussed in Sec. 1.5 the production of orthopositronium is only suppressed by the factor $(Z\alpha)^2$, which is not very small. Therefore one expects that both kind of positronium are produced in similar numbers. Detailed calculation show that the three-photon process is indeed not much smaller than the two-photon process [117, 118].

1.9 Event rates at CMS

An overview of the expected event rate for a number of different photon-photon reactions to either discrete states or continuum states is given in the following figures. The right hand axes shows both the number of events per second and per one-year run time (assuming 10^7 sec per year). We use beam luminosities of $10^{26} \text{cm}^{-2} \text{s}^{-1}$ for Pb-Pb and $4 \times 10^{30} \text{cm}^{-2} \text{s}^{-1}$ for Ca-Ca. The resonances have been calculated using the masses and photon-decay widths as given in table 1. For the calculation of the rate for a standard model Higgs boson H_{SM} , we use the approach as discussed in [73]. H' denotes a nonstandard Higgs as given in the “general two-Higgs doublet model”

in [77]. As its photon-photon decay width is rather weakly dependent on its mass in the relevant mass region, we have used a constant value of 0.1 keV in our calculations.

The total hadronic cross section $\sigma_{\gamma\gamma}(\text{hadron})$ was used in the form [60]:

$$\sigma_{\gamma\gamma}(\text{hadron}) = A(s/s_0)^\epsilon + B(s/s_0)^{-\eta} \quad (33)$$

with $s_0 = 1\text{GeV}^2$, $\epsilon = 0.079$, $\eta = 0.4678$, $A = 173\text{ nbarn}$, $B = 519\text{ nbarn}$. For the dilepton and $q\bar{q}$ production via $\gamma\gamma$, we have used the lowest order QED expression for pointlike fermions. For the quark masses we use $m_c = 1.3\text{ GeV}$ and $m_b = 4.6\text{ GeV}$ [119] (In this reference QCD corrections are also given). Of course these cross section only correspond to the “direct mechanism” (see Figure 7 above). In addition there will be also events coming from resolved processes as well as vector meson dominance [120, 121, 122]. This explains the much larger total hadronic cross section compared to the cross section due to the “direct mechanism”. These two-quark processes will be visible as two-jet events.

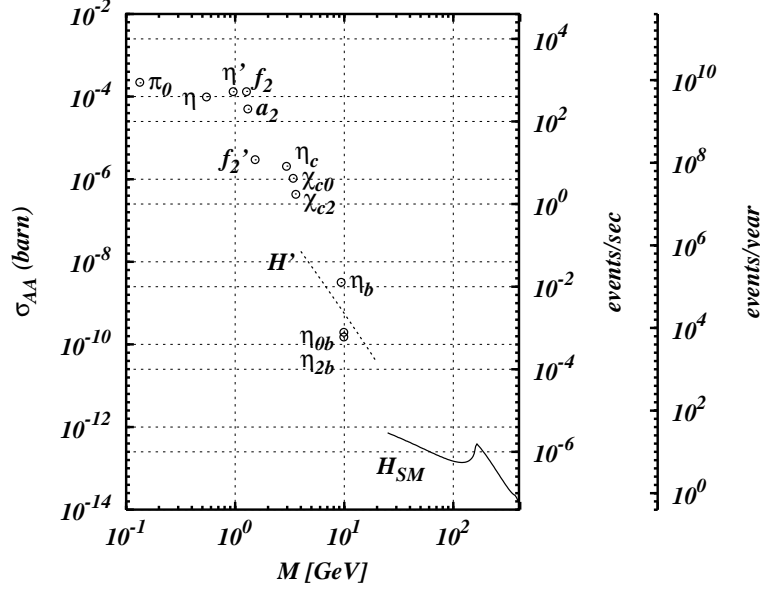


Figure 12: Overview of the total cross section and production rates (both per second and per one year run, assuming 1 year = 10^7 sec) of different resonances in Ca-Ca collisions at the CMS. We have used the parameters as given in the text and in table 1.

1.10 Selecting $\gamma\gamma$ -events

The $\gamma\gamma$ -luminosities are rather large, but the $\gamma\gamma \rightarrow X$ cross sections are small compared to their hadronic counterparts, therefore, e.g., the total hadronic production cross section for all events is still dominated by hadronic events. This makes it necessary to have an efficient trigger to distinguish photon-photon events from hadronic ones.

There are some characteristic features that make such a trigger possible. $\gamma\gamma$ -events are characterized by the fact that both nuclei remain intact after the interaction. Therefore a $\gamma\gamma$ -event will have the characteristic of a low multiplicity in the central region and no event in the very forward or backward direction (corresponding to fragments of the ions). The momentum transfer and energy loss for each ion are too small for the ion to leave the beam. It should be noted that in a $\gamma\gamma$ interaction with an invariant mass of several GeV leading to hadronic final states, quite a few particles will be produced, see, e.g., [60]

A second characteristic is the small transverse momenta of the produced system due to the coherence condition $q_\perp < 1/R \approx 50\text{ MeV}$. If one is able to make a complete reconstruction of the momenta of all produced particles with sufficient accuracy, this can be used as a very good suppression against grazing collisions. As the strong interaction is short ranged, it has normally a much broader distribution in the transverse momenta. A calculation using the PHOJET event generator [123] to study processes in central and grazing collisions by Pomeron-exchange found an average transverse momentum of about 450 MeV, about a factor of 10 larger than the $\gamma\gamma$ -events. In a study for the STAR experiment [124] it was also found that triggering for small transverse momenta is an efficient method to reduce the background coming from grazing collisions.

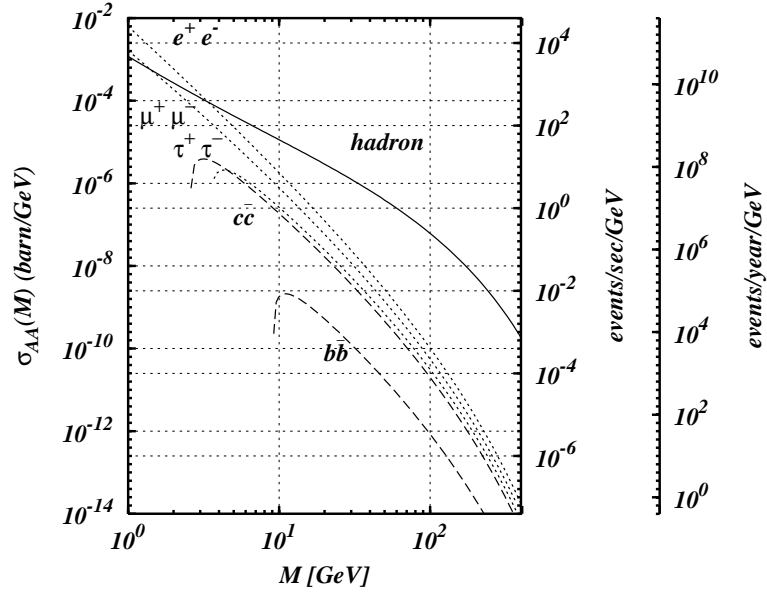


Figure 13: Overview of the total cross section and production rates (both per second and per one year run, assuming 1 year = 10^7 sec) per GeV for different dilepton and $q\bar{q}$ production for Ca-Ca collisions at CMS. Also shown is the total hadronic cross section. The parameters used are given in the text.

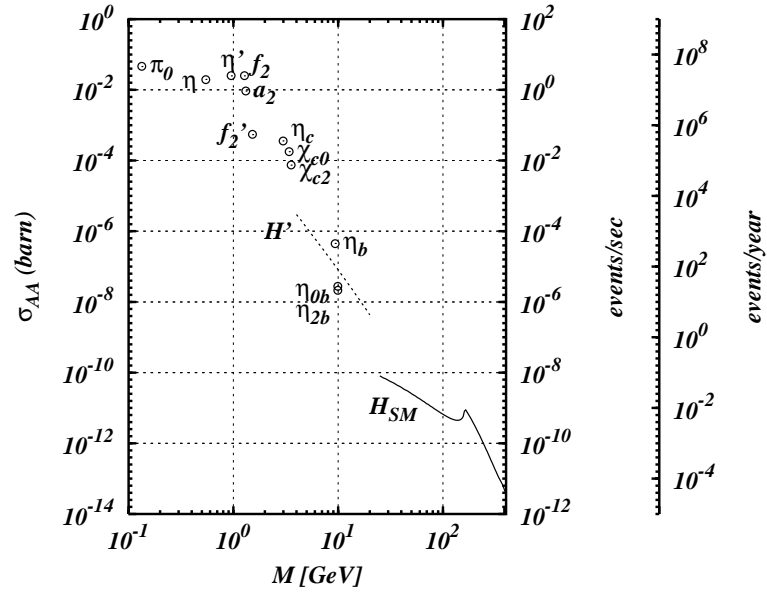


Figure 14: Overview of the total cross section and production rates (both per second and per one year run, assuming 1 year = 10^7 sec) of different resonances in Pb-Pb collisions at the CMS. We have used the parameters as given in the text and in table 1.

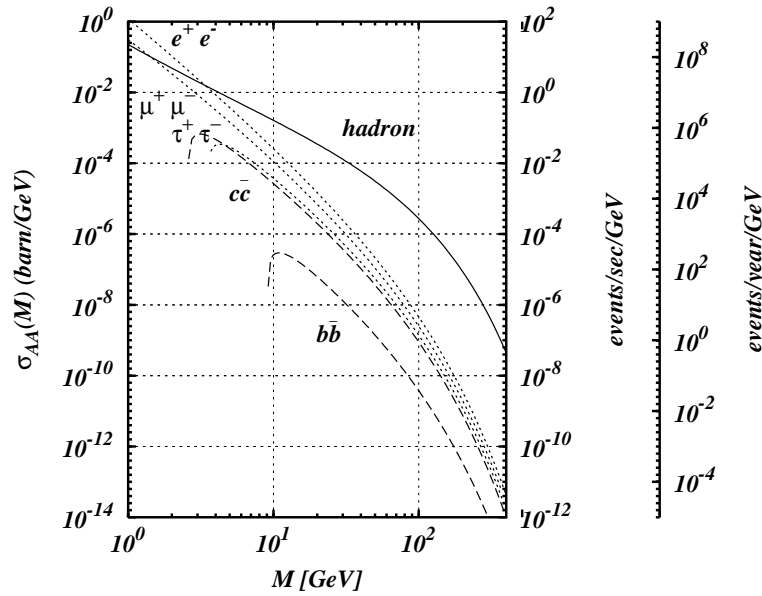


Figure 15: Overview of the total cross section and production rates (both per second and per one year run, assuming 1 year = 10^7 sec) per GeV for different dilepton and $q\bar{q}$ production for Pb-Pb collisions at CMS. Also shown is the total hadronic cross section. The parameters used are given in the text.

Another question that has to be addressed is the importance of diffractive events, that is, Photon-Pomeron and Pomeron-Pomeron processes in ion collisions. From experiments at HERA one knows that the proton has a large probability to survive intact after these collisions. The theoretical situation unfortunately is not very clear for these high energies and especially for nuclei as compared to nucleons. Some calculations within the dual parton model have been made and were interpreted as an indication that Photon-Pomeron and Pomeron-Pomeron events are of the same size or even larger than photon-photon events [123]. But these calculations were done without requiring the condition to have intact nuclei in the final state. As the nuclei are bound only rather weakly and as mentioned above the average momentum transfer to the nucleus is of the order of 200 MeV, it is very likely that the nucleus will break up in such a collision. First estimates based on this model indicate, that this leads to a substantial suppression of diffractive events, favoring again the photon-photon events.

The cross section ratio of photon-photon to Pomeron-Pomeron processes depends on the ion species. Roughly it scales with $Z^4/A^{1/3}$, see [31]. Thus for heavy ions, like Pb, we may expect dominance of the photon-photon processes whereas, say in pp -collisions, the Pomeron-Pomeron processes will definitely dominate in coherent collisions.

Nevertheless diffractive events are of interest in ion collisions too. As one is triggering again on an intact nucleus, one expects that the coherent Pomeron emission from the whole nucleus will lead to a total transverse momentum of the produced system similar to the $\gamma\gamma$ -events. Therefore one expects that part of the events are coming from diffractive processes. It is of interest to study how these could be further distinguished from the photon-photon events.

Another class of background events are additional electromagnetic processes. One of the dominating events here is the electromagnetic excitation of the ions due to an additional single-photon exchange. As mentioned above this is one of the dominant beam-loss processes for Pb-Pb collisions. The probability to excite at least one of the ions for Pb-Pb collisions is about 65% and about 2% for Ca-Ca for an impact parameter of $2R$. Especially at large invariant masses, $\gamma\gamma$ -events occur at impact parameter close to $2R$, therefore in the case of Pb-Pb collisions one has to expect that most of them are accompanied by the excitation or dissociation of one of the ions [40, 125]. Most of the excitation lead into the giant dipole resonance (GDR), which has almost all of the dipole strength. As it decays predominantly via the emission of a neutron, this leads to a relativistic neutron with an energy of about 3 TeV in the forward direction. Similarly all other low energy breakup reactions in the rest frame of one of the ions are boosted to high energy particles in the laboratory. In order to increase the $\gamma\gamma$ -luminosity it would be interesting to include these events also in the $\gamma\gamma$ -trigger. On the other hand one has to make sure, that this does not obscure the interpretation of these events as photon-photon events.

Another background process is the production of electron-positron pairs, see Sec. 1.8. Due to their small mass,

they are produced rather copiously. They are predominantly produced at low invariant masses and energies and in the forward and backward direction. Figure 16 shows cross section as a function of energy and angle for different experimental cuts. On the other hand, as the total cross section for this process is enormous (≈ 230 kbarn for Pb-Pb collisions, 800 barn for Ca-Ca collisions), a significant cross section remains even at high energies in the forward direction. This has to be taken into account when designing forward detectors. Table 3 shows the cross section for e^+e^- production where the energy of both particles is above a certain threshold value.

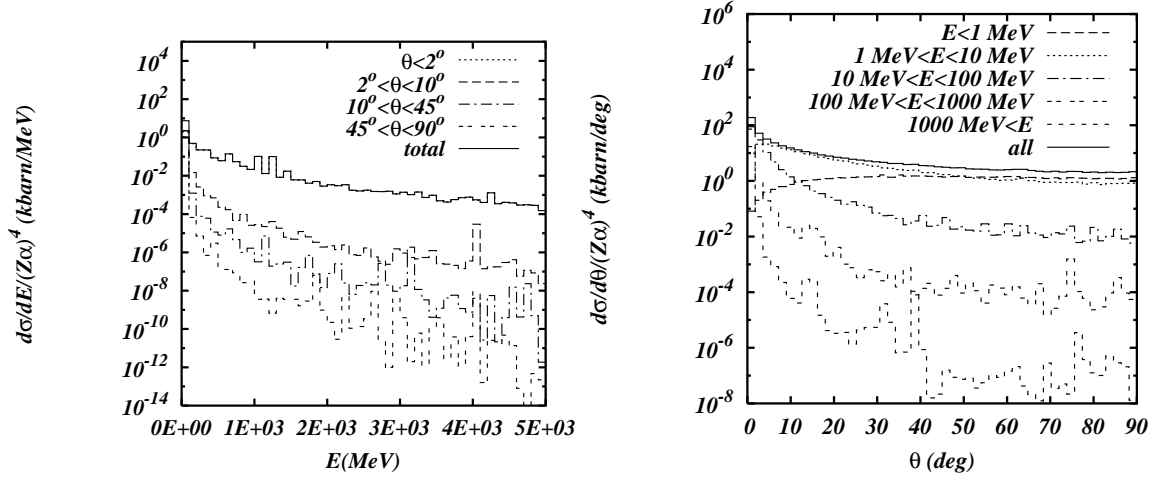


Figure 16: The single differential cross section for a number of experimental constraints. (a) for different angular-ranges as a function of energy, (b) for different energies as a function of the angle with the beam axis θ .

Table 3: Cross sections of e^+e^- pair production when *both* electron and positron have an energy above a threshold value.

E_{thr} (GeV)	$\sigma(\text{Pb-Pb})$	$\sigma(\text{Ca-Ca})$
0.25	3.5 kbarn	12 barn
0.50	1.5 kbarn	5.5 barn
1.0	0.5 kbarn	1.8 barn
2.5	0.08 kbarn	0.3 barn
5.0	0.03 kbarn	0.1 barn

1.11 Conclusion

In this contribution to the CMS heavy ion chapter the basic properties of peripheral hadron-hadron collisions are described. Electromagnetic processes, that is, photon-photon and photon-hadron collisions, are an interesting option, complementing the program for central collisions. It is the study of events, with relatively small multiplicities and a small background. These are good conditions to search for new physics. The method of equivalent photons is a well established tool to describe these kinds of reactions. Reliable results of quasireal photon fluxes and $\gamma\gamma$ -luminosities are available. Unlike electrons and positrons heavy ions and protons are particles with an internal structure. Effects arising from this structure are well under control and minor uncertainties coming from the exclusion of central collisions and triggering can be eliminated by using a luminosity monitor from muon- or electron-pairs. A trigger for peripheral collisions is essential in order to select photon-photon events. Such a trigger seems to be possible based on the survival of the nuclei after the collision and the use of the small transverse momenta of the produced system. A problem, which is difficult to judge quantitatively at the moment, is the influence of strong interactions in grazing collisions, i.e., effects arising from the nuclear stratosphere and Pomeron interactions.

The high photon fluxes open up possibilities for photon-photon as well as photon-nucleus interaction studies up to energies hitherto unexplored at the forthcoming colliders RHIC and LHC. Interesting physics can be explored at the high invariant $\gamma\gamma$ -masses, where detecting new particles could be within range. Also very interesting studies within the standard model, i.e., mainly QCD studies will be possible. This ranges from the study of the total

$\gamma\gamma$ -cross section into hadronic final states up to invariant masses of about 100 GeV to the spectroscopy of light and heavy mesons. The production via photon-photon fusion complements the production from single photons in e^+e^- collider and also in hadronic collisions via other partonic processes.

Peripheral collisions using Photon-Pomeron and Pomeron-Pomeron collisions, that is, diffractive processes are an additional application. They use essentially the same triggering conditions and therefore one should be able to record them at the same time as photon-photon events.

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